

# Shadows of Relic Neutrino Masses and Spectra on Highest Energy GZK Cosmic Rays

D.Fargion,<sup>1</sup> M.Grossi, P.G.De Sanctis Lucentini, C.Di Troia, R.V.Konoplich<sup>2</sup>

<sup>1</sup> Physics Department and INFN , Rome University 1,  
Pl.A.Moro 2, 00185, Rome, Italy

<sup>2</sup> Physics Dept.New York University,N.Y.,USA

**Abstract.** The Ultra High Energy (UHE) neutrino scattering onto relic cosmic neutrinos in galactic and local halos offers an unique way to overcome GZK cut-off. The  $UHE\nu$  secondary of  $UHE$  photo-pion decays may escape the  $GZK$  cut-off and travel on cosmic distances hitting local light relic neutrinos clustered in dark halos. The  $Z$  resonant production and the competitive  $W^+W^-$ ,  $ZZ$  pair production define a characteristic imprint on hadronic consequent UHECR spectra. This imprint keeps memory both of the primary  $UHE\nu$  spectra as well as of the possible relic neutrino masses values, energy spectra and relic densities. Such an hadronic showering imprint should reflect into spectra morphology of cosmic rays near and above GZK ( $10^{19} - 10^{21}$  eV) cut-off energies. A possible neutrino degenerate masses at  $eVs$  or a more complex and significant neutrino mass split below or near Super-Kamiokande  $\Delta m_{\nu_{SK}} \sim 0.1$ eV masses might be reflected after each corresponding  $Z$  peak showering, into new twin unexpected  $UHECR$  flux modulation behind  $GZK$  energies:  $E_p \sim 3 \left( \frac{\Delta m_{\nu_{SK}}}{m_\nu} \right) \cdot 10^{21}$  eV. Other extreme shadows of lightest, nearly massless, neutrinos  $m_{\nu_{2K}} \simeq 0.001$ eV  $\simeq kT_\nu$ , their lowest relic temperatures, energies and densities might be also reflected at even higher energies edges near Grand Unification:  $E_p \sim 2.2 \left( \frac{m_{\nu_{2K}}}{E_\nu} \right) \cdot 10^{23}$  eV.

## 1 Introduction

Modern astro-particle physics face the old standing problem of dark matter nature in galaxies up to cosmic scales. Neutrino with a light mass may play a relevant role in solving the puzzle within a hot-cold dark matter (HCDM) scenario. Moreover, at the edge of highest energy astrophysics, the main open question regards the nature of highest (Ultra High Energy, UHE) cosmic rays above the Greisen Zatsepin Kuzmin cut-off ( $\gtrsim 4 \cdot 10^{19}$  eV).

These rare events almost in isotropic spread are probably originated by blazars AGN, QSRs or GRBs in standard scenario, and they should not come, if originally of hadronic nature, from large distances because of the electromagnetic "dragging friction" of cosmic 2.75 K BBR and of the lower energy diffused intergalactic radio backgrounds. Indeed as noted by Greisen, Zatsepin and Kuzmin [1], [2], proton and nucleon mean free path at  $E > 5 \cdot 10^{19}$   $EeV$  is less than 30  $Mpc$  and asymptotically nearly ten  $Mpc$ ; also gamma rays at those energies have even shorter interaction length ( $10 Mpc$ ) due to severe opacity by electron pair production via microwave and radio background interactions [3]. Nevertheless these powerful sources (AGN, Quasars, GRBs) suspected to be the unique

source able to eject such UHECRs, are rare at nearby distances ( $(\lesssim 10 \div 20 \text{ Mpc})$  as for nearby  $M87$  in Virgo cluster); moreover there are not nearby *AGN* in the observed UHECR arrival directions. Strong and coherent galactic (Biermann 1999-2000) or extragalactic (Farrar and Tvi Piran 1999-2000) magnetic fields, able to bend such UHECR (proton, nuclei) directions are not really at hand. The needed coherent lengths and strength are not easily compatible with known cosmic data on polarized Faraday rotation. Finally in latter scenario the same contemporaneous ultra-high energy *ZeV* neutrons born, by photo-pion production on BBR, may escape the magnetic fields bending and should keep memory of the primordial nearby ( let say  $M87$ ) arrival direction, leading to (unobserved) in-homogeneities toward the primary source. Finally secondaries EeV photons (by neutral pion decays) should also abundantly point and cluster toward the same nearby *AGN* sources [4],[5] contrary to (never observed) *AGASA* data. Another solution of the present GZK puzzle, the Topological defects (*TD*), assumes as a source, relic heavy particles of early Universe; they are imagined diffused as a Cold Dark Matter component, in galactic or Local Group Halos . Nevertheless the *TD* fine tuned masses and ad-hoc decays are unable to explain the growing evidences of doublets and triplets clustering in *AGASA UHECR* arrival data. In this scenario there have been recent suggestions and speculations [6] for an unexpected population of such 500 compact dark clouds of  $10^8 M_\odot$ , each one made by such dark *TD* clusters, spread in our galactic halo ; they are assumed, nevertheless, not correlated to luminous known galactic halo, disk, globular clusters and center components. We found all these speculations unnatural and not plausible. On the other side there are possible evidences of correlation between UHECR arrival directions with far Compact Radio Loud Quasar at cosmic distance (above GZK cut-off) ( Amitabh 2000). Therefore the solution of UHECR puzzle based on primary Extreme High Energy (EHE) neutrino beams(from AGN) at  $E_\nu > 10^{21} \text{ eV}$  and their undisturbed propagation from cosmic distances up to nearby calorimeter made of relic light  $\nu$  in dark galactic or local dark halo (Fargion, Salis 1997;Fargion,Mele,Salis 1999, Weiler 1999, Yoshida et all 1998) is still, in our opinion, the most favorite conservative solution for the GZK puzzle. Interestingly new complex scenarios are then opening.

## 2 UHE neutrino scattering in the halo: the three neutrino masses, interaction scenarios

If relic neutrinos have a mass around an eVs they may cluster in galactic or Local Group halos, their scattering with incoming EHE neutrinos determine high energy particle cascades which could contribute or dominate the observed UHECR flux at *GZK* edges. Indeed the possibility that neutrino share a little mass has been reinforced by Super-Kamiokande evidence for atmospheric neutrino anomaly via  $\nu_\mu \leftrightarrow \nu_\tau$  oscillation. Consequently there are at least two main extreme scenario for hot dark halos: either  $\nu_\mu, \nu_\tau$  are both extremely light

( $m_{\nu_\mu} \sim m_{\nu_\tau} \sim \sqrt{(\Delta m)^2} \sim 0.07 \text{ eV}$ ) and therefore hot dark neutrino halo is very wide, possibly degenerated (Gelmini 2000) and spread out to local group clustering sizes (increasing the radius but loosing in the neutrino density clustering contrast), or  $\nu_\mu, \nu_\tau$  have degenerated (eV masses) split by a very tiny different value.

In the latter fine-tuned neutrino mass case ( $m_\nu \sim 0.4 \text{ eV} - 1.2 \text{ eV}$ ) (see Fig.2 and Fig.3) the Z peak  $\nu\bar{\nu}_r$  interaction (Fargion, Salis 1997; Fargion, Mele, Salis 1999, Weiler 1999, Yoshida et all 1998) will be the favorite one while in the second case for heavier non constrained neutrino mass ( $m_\nu \gtrsim 5 \text{ eV}$ ) only a  $\nu\bar{\nu}_r \rightarrow W^+W^-$  (Fargion, Mele, Salis 1999), and the additional  $\nu\bar{\nu}_r \rightarrow ZZ$  interactions, (see the cross-section in Fig.1) considered here for the first time, will be the only ones able to solve the GZK puzzle. Indeed the relic neutrino mass within HDM models in galactic halo near  $m_\nu \sim 4 \text{ eV}$ , corresponds to a "lower" and Z resonant incoming energy

$$E_\nu = \left( \frac{4 \text{ eV}}{\sqrt{m_\nu^2 + p_\nu^2}} \right) \cdot 10^{21} \text{ eV}.$$

This resonant incoming neutrino energy is able to shower only a small energy fraction into nucleons ( $p, \bar{p}, n, \bar{n}$ ), (see Tab.1 below), at energies  $E_p$  quite below GZK cut-off (see Tab.2 below).

$$E_p = 2.2 \left( \frac{4 \text{ eV}}{\sqrt{m_\nu^2 + p_\nu^2}} \right) \cdot 10^{19} \text{ eV}.$$

We usually may consider cosmological relic neutrinos in Standard Model at non relativistic regime neglecting  $p_\nu$  term. However, at lightest mass values the momentum may be comparable to the relic mass; moreover the spectra may reflect unexpected relic neutrino black bodies or gray body at energies much above the neutrino mass. Indeed there may be exist, within or beyond Standard Cosmology, a relic neutrino component due to stellar, Super Nova, GRBs, AGN activities red-shifted into a present KeV-eV relic neutrino grey-body energy spectra. Therefore it is worth-full to keep the most general mass and momentum term in the relic neutrino energy.

As we noticed above, relic neutrino mass above a few eVs in HDM halo are not consistent with Z peak; higher energies interactions ruled by WW,[19],[9] ZZ cross-sections may nevertheless solve the GZK cut-off. In this regime there will be also possible to produce by virtual W exchange, t-channel, *UHE* lepton pairs, by  $\nu_i\bar{\nu}_j \rightarrow l_i\bar{l}_j$ , leading to additional electro-magnetic showers injection. The hadronic tail of the Z or  $W^+W^-$  cascade is the source of final nucleons  $p, \bar{p}, n, \bar{n}$  able to explain UHECR events observed by Fly's Eye and AGASA [14] and other detectors. The same  $\nu\bar{\nu}_r$  interactions are source of Z and W that decay in rich shower ramification. The electro-magnetic showering will be discussed in detail else-where [13]. The average energy deposition for both gauge bosons among the secondary particles is summarized in Table 1

	Z	$W^+W^-$	t-channel
$\nu$	58 %	55 %	47 %
$\gamma$	21 %	21 %	4 %
$e^+e^-$	16 %	19 %	49 %
$p$	5 %	5 %	-

**Table 1.** Total Energy percentage distribution into neutrino, gamma, electron pairs particles (from Z and  $WW, ZZ$  as well as t-channel W decay), before energy losses. These UHE photons are mainly relics of neutral pions. Most of the  $\gamma$  radiation will be degraded around PeV energies by  $\gamma\gamma$  pair production with cosmic 2.75 K BBR, or with cosmic radio background. The electron pairs instead, are mainly relics of charged pions and will rapidly lose energies into synchrotron radiation

Although protons (or anti-protons, as well as neutron and anti-neutrons) are the most favorite candidate in order to explain the highest energy air shower observed, one doesn't have to neglect the signature of final electrons and photons. In fact electron (positron) interactions with the galactic magnetic field or soft radiative backgrounds may lead to gamma cascades and it may determine gamma signals from EeV, to MeV energies related to the same UHECR shower event .

Gamma photons at energies  $E_\gamma \simeq 10^{20} - 10^{19} \text{ eV}$  may freely propagate through galactic or local halo scales (hundreds of kpc to few Mpc) and could contribute to the extreme edges of cosmic ray spectrum [11][13].

The ratio of the final energy flux of nucleons near the Z peak resonance,  $\Phi_p$  over the corresponding electro-magnetic energy flux  $\Phi_{em}$  ratio is, as in tab.1  $e^+e^-$ ,  $\gamma$  entrance, nearly  $\sim \frac{1}{8}$ . Moreover if one considers at higher  $E_\nu$  energies, the opening of  $WW$ ,  $ZZ$  channels and the six pairs  $\nu_e\bar{\nu}_\mu$ ,  $\nu_\mu\bar{\nu}_\tau$ ,  $\nu_e\bar{\nu}_\tau$  (and their anti-particle pairs) t-channel interactions leading to highest energy leptons, with no nucleonic relics (as  $p, \bar{p}$ ), this additional injection favors the electro-magnetic flux  $\Phi_{em}$  over the corresponding nuclear one  $\Phi_p$  by a factor  $\sim 1.6$  leading to  $\frac{\Phi_p}{\Phi_{em}} \sim \frac{1}{13}$ . This ratio is valid at  $WW, ZZ$  masses because the overall cross section variability is energy dependent. At center of mass energies above these values, the  $\frac{\Phi_p}{\Phi_{em}}$  decreases more because the dominant role of t-channel (Fig1). We shall focus here on Z, and  $WW, ZZ$  channels showering in hadrons while their main consequent electro-magnetic showering will be discussed elsewhere [13].

Extragalactic neutrino cosmic rays are free to move on cosmic distances up our galactic halo without constraint on their mean free path, because the interaction length with cosmic background neutrinos is greater than the actual Hubble distance . A Hot Dark Matter galactic or local group halo model with relic light neutrinos (primarily the heaviest  $\nu_\tau$  or  $\nu_\mu$ ) [9], acts as a target for the high energy neutrino beams. The relic number density and the halo size are large enough to allow the  $\nu\nu_{relic}$  interaction . As a consequence high energy particle showers are produced in the galactic or local group halo, overcoming the GZK cut-off [9]. There is an upper bound density clustering for very light Dirac

fermions due to the maximal Fermi degeneracy whose adimensional density contrast is  $\delta\rho \propto m_\nu^3$ , [7],[9], while the neutrino free-streaming halo grows only as  $\propto m_\nu^{-1}$ . Therefore the overall interaction probability grows  $\propto m_\nu^2$ , favoring heavier non relativistic (eVs) neutrino masses. Nevertheless the same lightest relic neutrinos may share higher Local Group velocities (thousands  $\frac{Km}{s}$ ) or even nearly relativistic speeds and it may therefore compensate the common bound:

$$n_{\nu_i} = 10^3 \left( \frac{n_{\nu_i}}{54 \text{cm}^{-3}} \right) \left( \frac{m_i}{0.1 \text{eV}} \right)^3 \left( \frac{v_{\nu_i}}{2000 \frac{Km}{s}} \right)^3 \quad (3)$$

From the cross section side there are three main interaction processes that have to be considered leading to nucleons in the of EHE and relic neutrinos scattering.

**channel 1.** The  $\nu\nu_r \rightarrow Z \rightarrow$  annihilation at the Z resonance

**channel 2.**  $\nu_\mu \bar{\nu}_\mu \rightarrow W^+ W^-$  or  $\nu_\mu \bar{\nu}_\mu \rightarrow ZZ$  leading to hadrons, electrons, photons, through W and Z decay.

**channel 3.** The  $\nu_e - \bar{\nu}_\mu$ ,  $\nu_e - \bar{\nu}_\tau$ ,  $\nu_\mu - \bar{\nu}_\tau$  and hermite conjugate interactions of different flavor neutrinos mediated in the  $t$  - channel by the W exchange (i.e.  $\nu_\mu \bar{\nu}_{\tau_r} \rightarrow \mu^- \tau^+$ ). These reactions are sources of prompt and secondary UHE electrons as well as photons resulting by hadronic  $\tau$  decay.

## 2.1 The process $\nu_\tau \bar{\nu}_\tau \rightarrow Z$

The interaction of neutrinos of the same flavor can occur via a Z exchange in the  $s$ -channel ( $\nu_i \bar{\nu}_i$  and charge conjugated). The cross section for hadron production in  $\nu_i \bar{\nu}_i \rightarrow Z^* \rightarrow \text{hadrons}$  is

$$\sigma_Z(s) = \frac{8\pi s}{M_Z^2} \frac{\Gamma(Z^o \rightarrow \text{invis.}) \Gamma(Z^o \rightarrow \text{hadr.})}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2} \quad (4)$$

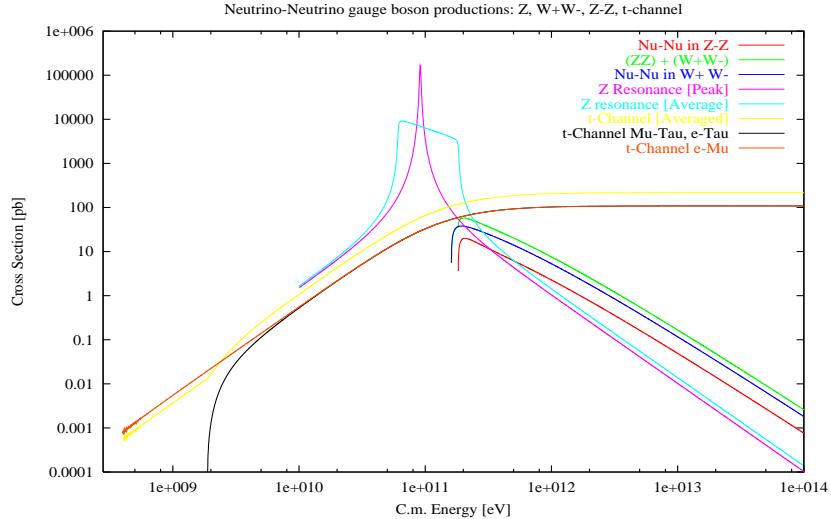
where  $\Gamma(Z^o \rightarrow \text{invis.}) \simeq 0.5 \text{ GeV}$ ,  $\Gamma(Z^o \rightarrow \text{hadr.}) \simeq 1.74 \text{ GeV}$  and  $\Gamma_Z \simeq 2.49 \text{ GeV}$  are respectively the experimental Z width into invisible products, the Z width into hadrons and the Z full width [18]. The averaged cross section peak reaches the value ( $\langle \sigma_Z \rangle = 4.2 \cdot 10^{-32} \text{ cm}^2$ ). We assumed here for a more general case (non relativistic and nearly relativistic relic neutrinos) that the averaged cross section has to be extended over an energy window comparable to half the center of mass energy. The consequent effective averaged cross-section is described in Fig.1 as a truncated hill curve.

A  $\nu\nu_r$  interaction mediated in the  $s$ -channel by the Z exchange, shows a peculiar peak in the cross section due to the resonant Z production at  $s = M_Z^2$ . However, this occurs for a very narrow and fine-tuned windows of arrival neutrino energies  $\nu_1$  (and of the corresponding target neutrino masses and momentum  $\bar{\nu}_1$ ):

$$E_{\nu_i} = \left( \frac{4eV}{\sqrt{m_{\nu_i}^2 + p_{\nu_i}^2}} \right) \cdot 10^{21} eV. \quad (5)$$

So in this mechanism the energy of the EHE neutrino cosmic ray is related to the mass of the relic neutrinos, and for an initial neutrino energy fixed at  $E_\nu \simeq 10^{22} eV$ , the Z resonance requires a mass for the heavier neutral lepton around  $m_\nu \simeq 0.4 eV$ . Apart from this narrow resonance peak at  $\sqrt{s} = M_Z$ , the asymptotic behaviour of the cross section is proportional to  $1/s$  for  $s \gg M_Z^2$ .

The  $\nu\bar{\nu} \rightarrow Z \rightarrow \text{hadrons}$  reactions have been proposed by [8] [10] [11] with a neutrino clustering on Supercluster, cluster, Local Group, and galactic halo scale within the few tens of Mpc limit fixed by the GZK cut-off. Due to the enhanced annihilation cross-section in the Z pole, the probability of a neutrino collision is reasonable even for a low neutrino density contrast  $\delta\rho_\nu/\rho_\nu \geq 10^3$ . The potential wells of such structures might enhance the neutrino local density with an efficiency at comparable with observed baryonic clustering discussed above.



**Fig. 1.** The  $\nu\bar{\nu} \rightarrow Z, W^+W^-, ZZ, T\text{-channel}$ , cross sections as a function of the center of mass energy in  $\nu\bar{\nu}$ . These cross-sections are estimated also in average (Z) as well for each possible t-channel lepton pairs. The averaged t-channel averaged the multiplicity of flavours pairs  $\nu_i, \bar{\nu}_j$  respect to neutrino pair annihilations into Z neutral boson.

## 2.2 The processes $\nu_\tau\bar{\nu}_\tau \rightarrow W^+W^-$ and $\nu_\tau\bar{\nu}_\tau \rightarrow ZZ$

The reactions  $\nu_\tau\bar{\nu}_\tau \rightarrow W^+W^-$ ,  $\nu_\mu\bar{\nu}_\mu \rightarrow W^+W^-$ ,  $\nu_e\bar{\nu}_e \rightarrow W^+W^-$ , that occurs through the exchange of a Z boson (s channel)) [19], has been previously intro-

duced [9] in order to explain UHECR as the Fly's Eye event at 320 Eev detected in 1991 and last AGASA data. The cross section is given by [9]

$$\sigma_{WW}(s) = \sigma_{asym} \frac{\beta_W}{2s} \frac{1}{(s - M_Z^2)} \{4L(s) \cdot C(s) + D(s)\} \quad (6)$$

where  $\beta_W = (1 - 4M_W^2/s)^{1/2}$ ,  $\sigma_{asym} = \frac{\pi\alpha^2}{2\sin^4\theta_W M_W^2} \simeq 108.5 \text{ pb}$ , and the functions  $L(s)$ ,  $C(s)$ ,  $D(s)$  are defined as

$$\begin{aligned} L(s) &= \frac{M_W^2}{2\beta_W s} \ln \left( \frac{s + \beta_W s - 2M_W^2}{s - \beta_W s - 2M_W^2} \right) \\ C(s) &= s^2 + s(2M_W^2 - M_Z^2) + 2M_W^2(M_Z^2 + M_W^2) \\ D(s) &= \frac{1}{12M_W^2(s - M_Z^2)} \times \left[ s^2(M_Z^4 - 60M_W^4 - 4M_Z^2M_W^2) + \right. \\ &\quad \left. + 20M_Z^2M_W^2s(M_Z^2 + 2M_W^2) - 48M_Z^2M_W^4(M_Z^2 + M_W^2) \right]. \end{aligned} \quad (7)$$

This result should be compared with the additional new ZZ interaction channel considered for the first time here:

$$\sigma_{ZZ} = \frac{G^2 M_Z^2}{4\pi} y \frac{(1 + \frac{y^2}{4})}{(1 - \frac{y}{2})} \left\{ \ln \left[ \frac{2}{y} \left( 1 - \frac{y}{2} + \sqrt{1 - y} \right) \right] - \sqrt{1 - y} \right\} \quad (8)$$

$$\text{where } y = \frac{4M_Z^2}{s} \text{ and } \frac{G^2 M_Z^2}{4\pi} = 35.2 \text{ pb.}$$

Their values are plotted in Fig.1. The asymptotic behaviour of these cross section is proportional to  $\sim (\frac{M_W^2}{s}) \ln(\frac{s}{M_W^2})$  for  $s \gg M_Z^2$ .

The nucleon arising from WW and ZZ hadronic decay could provide a reasonable solution to the 320 Eev event puzzle. We'll assume that the fraction of pions and nucleons related to the total number of particles from the W boson decay is the almost the same of Z boson. So W hadronic decay ( $P \sim 0.68$ ) leads on average to about 37 particles, where  $\langle n_{\pi^0} \rangle \sim 9.19$ ,  $\langle n_{\pi^\pm} \rangle \sim 17$ , and  $\langle n_{p, \bar{p}, n, \bar{n}} \rangle \sim 2.7$ . In addition we have to expect by the subsequent decays of  $\pi$ 's (charged and neutral), kaons and resonances ( $\rho$ ,  $\omega$ ,  $\eta$ ) produced, a flux of secondary UHE photons and electrons.

As we already pointed out, the particles resulting from the decay are mostly prompt pions. The others are particles whose final decay likely leads to charged and neutral pions as well. As a consequence the electrons and photons come from prompt pion decay.

On average it results [18] that the energy in the bosons decay is not uniformly distributed among the particles, so that proton energy is about three times that of the direct pions. Each charged pion will give an electron (or positron) and

three neutrinos, that will have less than one per cent of the initial W boson energy, while each  $\pi^0$  decays in two photons, each with 1 per cent of the initial W energy. In the Table1 below we show all the channels leading from single Z,W and Z pairs as well as t-channel in nuclear and electro-magnetic components. Their energies and corresponding fluence are summarized in Table 2.

### 2.3 The process $\nu_i \nu_j \rightarrow l_i l_j$ : the t-channel

The processes  $\nu_i \nu_j \rightarrow l_i l_j$  (like  $\nu_\mu \nu_\tau \rightarrow \mu \tau$  for example)<sup>1</sup> occur through the W boson exchange in the t-channel. The cross-section has been derived in [9], while the energy threshold depends on the mass of the heavier lepton produced,  $E_{\nu_{th}} = 7.2 \cdot 10^{19} (m_\nu/0.4 \text{ eV})^{-1} (m_\tau/m_{\tau,\mu,e})$ , with the term  $(m_\tau/m_{\tau,\mu,e})$  including the different thresholds in all the possible interactions:  $\nu_\tau \nu_\mu$  (or  $\nu_\tau \nu_e$ ),  $\nu_\mu \nu_e$ , and  $\nu_e \nu_e$ . In the ultrarelativistic limit ( $s \simeq 2E_\nu m_{\nu_r} \gg M_W^2$  where  $\nu_r$  refers to relic clustered neutrinos) the cross-section tends to the asymptotic value  $\sigma_{\nu \bar{\nu}_r} \simeq 108.5 \text{ pb}$ .

$$\sigma_W(s) = \sigma_{asym} \frac{A(s)}{s} \left\{ 1 + \frac{M_W^2}{s} \left[ 2 - \frac{s + B(s)}{A(s)} \ln \left( \frac{B(s) + A(s)}{B(s) - A(s)} \right) \right] \right\} \quad (9)$$

where  $\sqrt{s}$  is the center of mass energy, the functions A(s), B(s) are defined as

$$A(s) = \sqrt{[s - (m_\tau + m_\mu)^2][s - (m_\tau - m_\mu)^2]} ; B(s) = s + 2M_W^2 - m_\tau^2 - m_\mu^2 \quad (10)$$

and

$$\sigma_{asym} = \frac{\pi \alpha^2}{2 \sin^4 \theta_W M_W^2} \simeq 108.5 \text{ pb} \quad (11)$$

where  $\alpha$  is the fine structure constant and  $\theta_W$  the Weinberg angle.  $\sigma_{asym}$  is the asymptotic behaviour of the cross section in the ultrarelativistic limit

$$s \simeq 2E_\nu m_\nu = 2 \cdot 10^{23} (E_\nu/10^{22} \text{ eV}) (m_\nu/10 \text{ eV}) \text{ eV}^2 \gg M_W^2 \quad . \quad (12)$$

This interactions, as noted in Table.1 are leading to electro-magnetic showers and are not offering any nuclear secondary. Their astrophysical role will be discussed elsewhere [13].

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<sup>1</sup> We could consider as well the reactions  $\nu_e \bar{\nu}_{\tau_r} \rightarrow e^- \tau^+$ ,  $\nu_e \bar{\nu}_{\mu_r} \rightarrow e^- \mu^+$  and  $\nu_e \bar{\nu}_{e_r} \rightarrow e^- e^+$ , changing the target or the high energy neutrino. Therefore there are 2 times more target than for Z, WW, ZZ channels.

### 3 The prediction of the UHE particles spectra from W and Z decay

Let us examine the destiny of UHE primary particles (nucleons, electrons and photons) ( $E_e \lesssim 10^{21} \text{ eV}$ ) produced after hadronic or leptonic W decay. As we already noticed in the introduction, we'll assume that the nucleons, electrons and photons spectra (coming from W or Z decay) after  $\nu\nu$  scattering in the halo, follow a power law that in the center of mass system is  $\frac{dN^*}{dE^*dt^*} \simeq E^{*-\alpha}$  where  $\alpha \sim 1.5$ . This assumption is based on detailed Monte Carlo simulation of a heavy fourth generation neutrino annihilations [15] [16] and with the model of quark - hadron fragmentation spectrum suggested by Hill [20].

In order to determine the shape of the particle spectrum in the laboratory frame, we have to introduce the Lorentz relativistic transformations from the center of mass system to the laboratory system.

The number of particles is clearly a relativistic invariant  $dN_{lab} = dN^*$ , while the relation between the two time intervals is  $dt_{lab} = \gamma dt^*$ , the energy changes like  $\epsilon_{lab} = \gamma \epsilon^*(1 + \beta \cos \theta^*) = \epsilon^* \gamma^{-1} (1 - \beta \cos \theta)^{-1}$ , and finally the solid angle in the laboratory frame of reference becomes  $d\Omega_{lab} = \gamma^2 d\Omega^* (1 - \beta \cos \theta)^2$ . Substituting these relations one obtains

$$\begin{aligned} \left( \frac{dN}{d\epsilon dt d\Omega} \right)_{lab} &= \frac{dN_*}{d\epsilon_* dt_* d\Omega_*} \gamma^{-2} (1 - \beta \cos \theta)^{-1} = \frac{\epsilon_*^{-\alpha} \gamma^{-2}}{4\pi} \cdot (1 - \beta \cos \theta)^{-1} \\ \left( \frac{dN}{d\epsilon dt d\Omega} \right)_{lab} &= \frac{\epsilon^{-\alpha} \gamma^{-\alpha-2}}{4\pi} (1 - \beta \cos \theta)^{-\alpha-1} \end{aligned} \quad (14)$$

and integrating on  $\theta$  (omitting the lab notation) one loses the spectrum dependence on the angle.

The consequent fluence derived by the solid angle integral is:

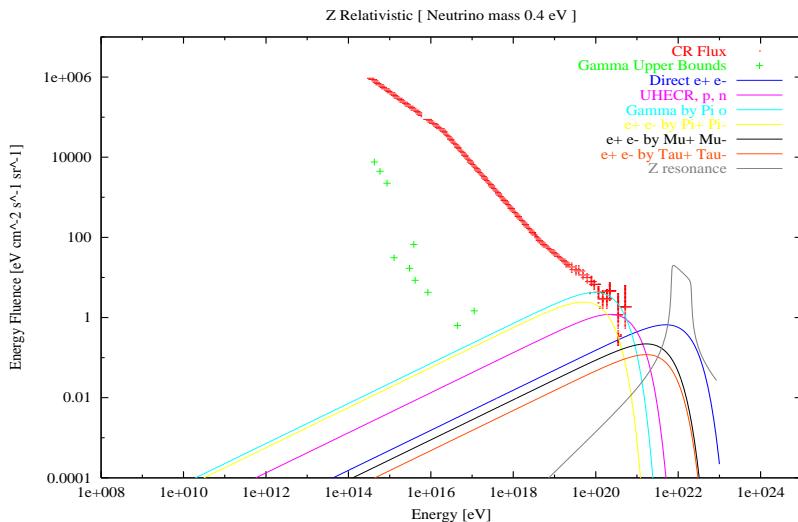
$$\frac{dN}{d\epsilon dt} \epsilon^2 = \frac{\epsilon^{-\alpha+2} \gamma^{\alpha-2}}{2\beta\alpha} [(1 + \beta)^\alpha - (1 - \beta)^\alpha] \simeq \frac{2^{\alpha-1} \epsilon^{-\alpha+2} \gamma^{\alpha-2}}{\alpha} \quad (15)$$

There are two extreme cases to be considered: the case where the interaction occurs at Z peak resonance and therefore the center of mass Lorentz factor  $\gamma$  is "frozen" at a given value (eq.1) and the case (WW,ZZ pair channel) where all energies are allowable and  $\gamma$  is proportional to  $\epsilon^{1/2}$ . Here we focus only on Z peak resonance. The consequent fluence spectra  $\frac{dN}{d\epsilon dt} \epsilon^2$ , as above, is proportional to  $\epsilon^{-\alpha+2}$ . Because  $\alpha$  is nearly 1.5 all the consequent secondary particles will also show a spectrum proportional to  $\epsilon^{1/2}$  following a normalized energies shown in Tab.2, as shown in Fig.(2-6). In the latter case (WW,ZZ pair channel), the relativistic boost reflects on the spectrum of the secondary particles, and the spectra power law becomes  $\propto \epsilon^{\alpha/2+1} = \epsilon^{0.25}$ . These channels will be studied in details elsewhere. In Fig. 1 we show the spectrum of protons, photons and electrons coming from Z hadronic and leptonic decay assuming a nominal primary CR energy flux  $\sim 20 \text{ eV s}^{-1} \text{ sr}^{-1} \text{ cm}^{-2}$ , due to the total  $\nu\bar{\nu}$  scattering at

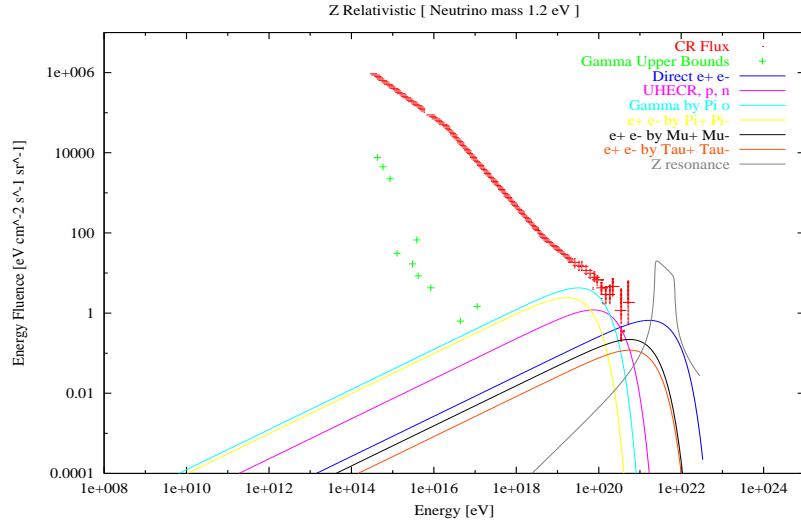
GZK energies as shown in figures 2-6. Let us remind that we assume an interaction probability of  $\sim 1\%$  and a corresponding UHE incoming neutrino energy  $\sim 2000\text{eV}\text{s}^{-1}\text{sr}^{-1}\text{cm}^{-2}$  near but below present *UHE* neutrino flux bound.

$Z_{decay}$	$E$ (eV)	$\frac{dN}{dE} E^2$ (eV)
p	$2.2 \cdot 10^{20}$	1.2
$\gamma$	$9.5 \cdot 10^{19}$	4.25
$e_\pi$	$5 \cdot 10^{19}$	2.4
$e_{prompt}$	$5 \cdot 10^{21}$	0.66
$e_\mu$	$1.66 \cdot 10^{21}$	0.23
$e_\tau$	$1.66 \cdot 10^{21}$	0.12

**Table 2.** Energy peak and Energy Fluence for different decay channels as described in the text.



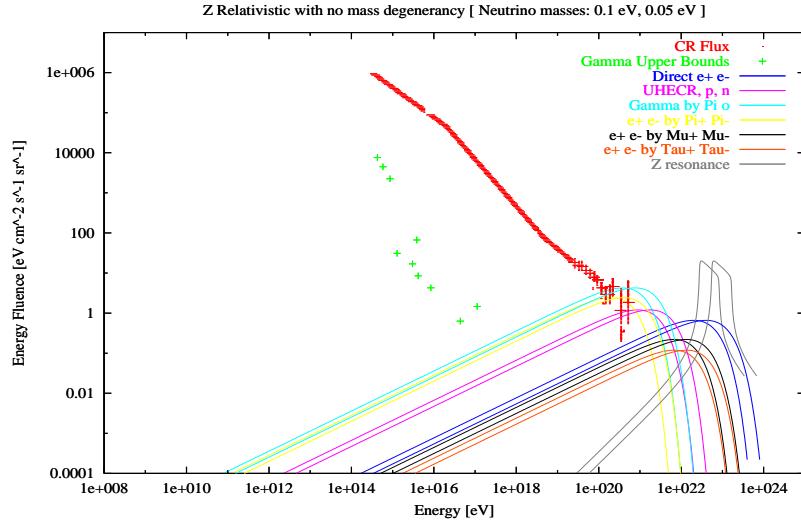
**Fig. 2.** Energy Fluence derived by  $\nu\bar{\nu} \rightarrow Z$  and its showering into different channels: direct electron pairs UHECR nucleons  $n$   $p$  and anti-nucleons,  $\gamma$  by  $\pi^0$  decay, electron pair by  $\pi^+\pi^-$  decay, electron pairs by direct muon and tau decays as labeled in figure. The relic neutrino mass has been assumed to be fine tuned to explain GZK UHECR tail:  $m_\nu = 0.4\text{eV}$ . The "Z resonance ghost" curve, derived from averaged cross-section in Fig.1, shows the averaged  $Z$  resonant cross-section peaked at  $E_\nu = 10^{22}\text{eV}$ . Each channel shower has been normalized following table 2.



**Fig. 3.** Energy Fluence derived by  $\nu\bar{\nu} \rightarrow Z$  and its showering into different channels as in previous Figure 2: direct electron pairs UHECR nucleons  $n$   $p$ ,  $\gamma$  by  $\pi^0$  decay, electron pair by  $\pi^+\pi^-$  decay, electron pairs by direct muon and tau decays as labeled in figure. In the present case the relic neutrino mass has been assumed to be fine tuned to explain GZK UHECR tail:  $m_\nu = 1.2\text{eV}$  with the same UHE incoming neutrino fluence of previous figure. The "Z resonance" curve shows the averaged Z resonant cross-section peaked at  $E_\nu = 3.33 \cdot 10^{21}\text{eV}$ . Each channel shower has been normalized in analogy to table 2.

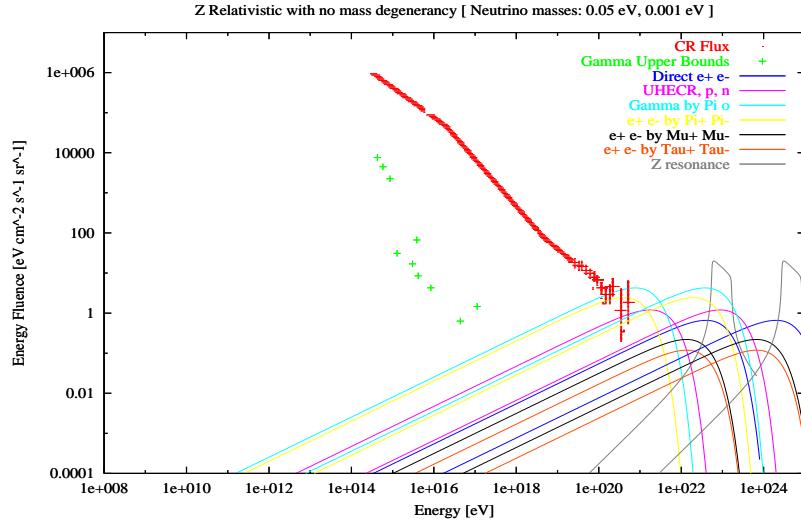
#### 4 Conclusion

UHECR above GZK may be naturally born by UHE  $\nu$  scattering on relic ones. They keep, as observed, memory of distant source direction naturally in agreement with the recent discoveries of triplets and doublets in UHECR spectra. The target cosmic  $\nu$  may be light and dense as the needed ones in HDM model (few eV). Then their  $W^+W^-$ ,  $ZZ$  pair production channel and not the  $Z$  resonant peak, would solve the GZK puzzle. At a much lighter, but fine tuned case  $m_\nu \sim 0.4\text{eV}$ ,  $m_\nu \sim 1.5\text{eV}$  assuming  $E_\nu \sim 10^{22}\text{eV}$ , one is able to solve at once the known UHECR data at GZK edge by the dominant  $Z$  peak; in this peculiar scenario one may foresee (fig.2-3) a rapid decrease (an order of magnitude in energy fluence) above  $3 \cdot 10^{20}\text{eV}$  in future data and a further recover (due to  $WW$ ,  $ZZ$  channels) at higher energies. The characteristic UHECR fluxes will reflect the averaged neutrino-neutrino interactions shown in Fig.1. Their imprint could confirm the neutrino mass value and relic density. At a more extreme lighter neutrino mass, occurring for  $m_\nu \sim m_{\nu_{SK}} \sim 0.07\text{eV}$ , the minimal  $m_{\nu_\tau}$ ,  $m_{\nu_\mu}$  small mass differences might be reflected, in a spectacular way, into UHECR modulation quite above the GZK edges. Therefore each different neutrino mass require a different incoming resonant  $Z$  peak  $E_\nu$  energy around



**Fig. 4.** Energy Fluence derived by  $\nu\bar{\nu} \rightarrow Z$  and its showering into different channels: direct electron pairs UHECR nucleons  $n$   $p$ ,  $\gamma$  by  $\pi^0$  decay, electron pair by  $\pi^+\pi^-$  decay, electron pairs by direct muon and tau decays as labeled in figure. In the present case the relic neutrino masses have been assumed with no degeneracy. The their values have been fine tuned to explain GZK UHECR tail:  $m_{\nu_1} = 0.1\text{eV}$  and  $m_{\nu_2} = 0.05\text{eV}$ . No relic neutrino density difference has been assumed. The incoming UHE neutrino fluence has been increased by a factor 2 respect previous Fig.2-3. The "Z resonance" curve shows the averaged  $Z$  resonant cross-section peaked at  $E_{\nu_1} = 4 \cdot 10^{22}\text{eV}$  and  $E_{\nu_2} = 8 \cdot 10^{22}\text{eV}$ . Each channel shower has been normalized in analogy to table 2.

$3 \cdot 10^{20} - 3 \cdot 10^{21}\text{eV}$  UHECR energies. These "twin" lightest masses (Fig.4) call for either gravitational  $\nu$  clustering above the expected one [12] or the presence of relativistic diffused background. The upper bound to black body neutrino Temperature and momentum, in a radiation dominated Universe, is nearly  $60K^\circ$ . Such energies and comparable masses (a few thousands of eV as the required ones in solar neutrino puzzle) are leading to an fore-see-able scenario described by Fig 5-6. However possible gray body spectra, out of thermal equilibrium, at higher energies may also arise from non standard early Universe. One may be wonder if such a diffused and homogeneous relic backgrounds are not leading by themselves to a new  $\nu - \nu$ GZK cut-off. This is not in general the case; other obvious signatures must also be manifest [13]. Therefore the solution of  $\nu\nu$  scattering at UHECR may probe the real value  $\nu$  density (calibrating the observed UHECR flux intensity) revealing the known cross-sections imprint (as in Fig 1) as well as their possible lightest neutrino mass splitting reflected in additional near future (Fig4) and (or) far future (Fig.5-6) UHECR new knee and ankles, just near and above GZK cut off. These energies are at Grand Unification edges. Of course the mystery of the UHECR acceleration is not yet solved, but their propagation from far cosmic volumes is finally allowed. Therefore the new gener-

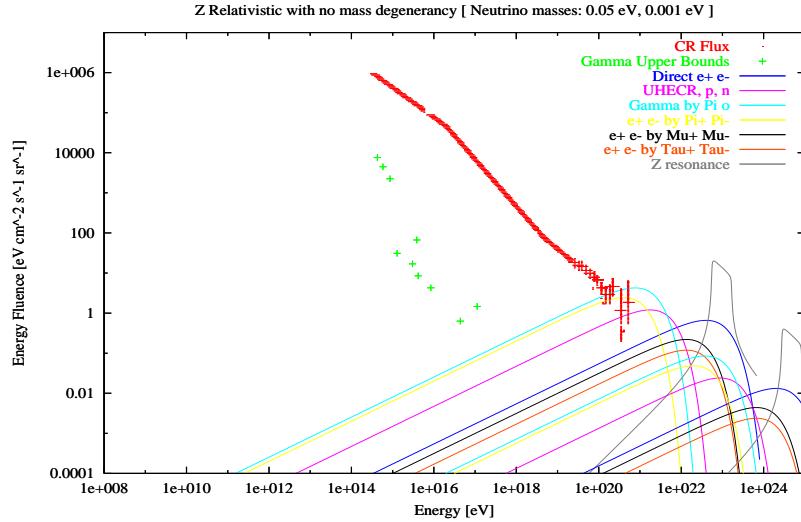


**Fig. 5.** Energy Fluence derived by  $\nu\bar{\nu} \rightarrow Z$  and its showering into different channels as above. In the present extreme case the relic neutrino masses have been assumed with wide mass differences just compatible both with Super-Kamiokande and relic  $2K^\circ$  Temperature. The their values have been fine tuned to explain observed GZK-UHECR tail:  $m_{\nu_1} = 0.05\text{eV}$  and  $m_{\nu_2} = 0.001\text{eV}$ . No relic neutrino density difference between the two masses has been assumed, contrary to bound in eq.3. The incoming UHE neutrino fluence has been increased by a factor 2 respect previous Fig.2-3. The "Z resonance" curve shows the averaged  $Z$  resonant cross-section peaked at  $E_{\nu_1} = 8 \cdot 10^{22}\text{eV}$  and  $E_{\nu_2} = 4 \cdot 10^{24}\text{eV}$ , just near Grand Unification energies. Each channel shower has been normalized in analogy to table 2.

ation UHECR signature within next decade, may offer the best probe in testing the lightest elementary particle masses, their relic densities and energies and the most ancient and evasive fingerprint of  $\nu$  cosmic relic background.

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**Fig. 6.** Energy Fluence derived by  $\nu\bar{\nu} \rightarrow Z$  and its showering into different channels as above. In the present extreme case the relic neutrino masses have been assumed with wide mass differences just compatible both with Super-Kamiokande and relic  $2K^\circ$  Temperature. The their values have been fine tuned to explain observed GZK-UHECR tail:  $m_{\nu_1} = 0.05\text{eV}$  and  $m_{\nu_2} = 0.001\text{eV}$ . A neutrino density difference between the two masses has been assumed, considering the lightest  $m_{\nu_2} = 0.001\text{eV}$  neutrino at relativistic regime, consistent to bound in eq.3. The incoming UHE neutrino fluence has been assumed growing linearly [11] with energy. Its value is increased by a factor 2 and 20 at  $E_{\nu_1} = 8 \cdot 10^{22}\text{eV}$  and  $E_{\nu_2} = 4 \cdot 10^{24}\text{eV}$  respect the previous ones Fig.2-3. The "Z resonance" curve shows its averaged Z resonant "ghost" cross-section peaked at  $E_{\nu_1} = 2 \cdot 10^{23}\text{eV}$  and  $E_{\nu_2} = 4 \cdot 10^{24}\text{eV}$ , just near Grand Unification energies. Each channel shower has been normalized in analogy to table 2.

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